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Management of teeth with vital pulps and open apices

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One of the main functions of the dental pulp is the formation of dentin. When the pulp undergoes pathological changes before complete root development, normal root growth is disrupted. If the pulp is reversibly inflamed due to caries or exposure, the treatment of choice is to maintain pulp vitality by pulp capping or pulpotomy. If the pulp is irreversibly inflamed or necrotic, traditional apexification procedures consist of multiple and long-term applications of calcium hydroxide in order to create an apical barrier that aids in root canal obturation. Recently, artificial apical barriers using mineral trioxide aggregate (MTA) have been introduced. In addition, pulp regeneration (revascularization) has received attention as an option for such teeth. That topic will be addressed in the next chapter. In this review, we will give a brief description of the embryology of root development, major causes of pulpal inflammation, factors affecting treatment planning, and tests for diagnosing pulpal conditions. This will be followed by a comprehensive literature review from 1908 through June 2010 regarding the definition, history, materials used, animal and human studies, mechanisms of action, prognosis, as well as advantages and disadvantages of apexogenesis by pulp capping and pulpotomy.

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Introduction

One of the primary functions of the dental pulp is the formation of dentin. As part of tooth formation, the apical opening gradually decreases in width during the period 3–4 years after tooth eruption (1). However, when the pulp undergoes pathological changes before complete root development, dentin formation and root growth cease. Pulpal status and degree of root development are the major factors in treatment planning for teeth with pulp pathosis (1). If the pulpal diagnosis is reversible pulpitis, the treatment of choice is vital pulp therapy that includes pulp capping and pulpotomy. If the diagnosis is irreversible pulpitis or pulp necrosis, the amount of root development will determine the proper treatment. If the apex is closed, root canal treatment is indicated (2,3).

The purpose of this review is to present information regarding a comprehensive list of articles from 1908 through June 2010 with respect to the definition, history, materials used, animal and human studies, mechanism of action, prognosis, as well as advantages and disadvantages of various procedures for treating teeth with vital pulps and open apices. The next chapter will address the topic of immature teeth with irreversible pulpitis and pulp necrosis.

Inclusion criteria

All publications related to the treatment of teeth with vital pulps and open apices from peer-reviewed journals and books published in English from 1908 through June 2010 are included.

Search methodology

An electronic search was conducted in the PubMed and Cochrane databases with appropriate MeSH headings and key words related to the treatment of teeth with vital pulps and open apices. To enrich the results, a manual search was conducted of the last two years' worth of issues of the following major endodontic journals: *International Endodontic Journal*; *Journal*

of Endodontics; and *Oral Surgery, Oral Medicine, Oral Pathology, Oral Radiology and Endodontology*. The process of cross-referencing continued until no new articles were identified. In addition, materials from textbooks related to the subjects were also included.

Tooth formation

Dentin and pulp are both involved in tooth development and are functionally integrated as one tissue, maintaining the anatomical and physiological functions of the tooth (4–6). The principles that guide embryonic tooth development are shared in common with other organs, but the most important developmental events are those guiding epithelial–mesenchymal interactions, which involve and promote molecular cross-talk and interaction between the ectoderm and mesenchyme, two tissues that have different origins (7,8).

Pulp tissue originates from ectomesenchymal cells (derived from the neural crest) of the dental papilla and is identified when these cells mature and dentin has formed. Dental epithelium is an example of a craniofacial ectodermal region that has a special ability to induce the underlying ectomesenchyme to develop into a particular structure. The dental epithelium induces the underlying receptive ectomesenchyme to condense and ultimately differentiate into dentin-forming cells (odontoblasts), which then induce the overlying dental epithelium to differentiate into enamel-forming cells (9).

The formation of dentin by odontoblasts heralds the conversion of dental papilla into dental pulp. Deposition progresses in a cervical (apical) direction in a rhythmic, regular pattern (10). As crown formation occurs, vascular and sensory neural elements begin migrating into the pulp in a coronal direction. This usually occurs after the tooth has erupted and root formation is nearly complete (11).

Root development commences after the completion of enamel formation. In the forming root, the presence of the first dentin against the epithelial root sheath signals retardation of the ectoderm. The dentino–enamel and dentino–cemental junctions are now established (12). Maturation of the dental papilla moves similar to a tide from the tooth's most coronal levels to its root apex. The cells of the inner and outer enamel unite at a point known as the cervical loop. This delineates the end of the anatomical crown and the site where root formation begins. It is initiated by the apical proliferation of the two epithelial structures, which combine at the cervical loop to form a double layer of cells known as Hertwig's epithelial root sheath. The function of this sheath is similar to that of the inner enamel epithelium during crown formation. It provides the stimulus for the differentiation of odontoblasts, which form the dentin and the template to which the dentin is formed.

Shortly after the first dentin (mantle dentin) has formed, fragmentation of Hertwig's epithelial root sheath occurs. This allows the initiation of a cellular cementum formation that will serve in developing principal periodontal fibers (13). As the epithelial root sheath proliferates and more dental papilla is enclosed, the end of the anatomical root becomes smaller and more eccentric. Apical root closure is completed approximately 3–4 years after tooth eruption (1,12).

Major causes of pulpal diseases

The major irritants of pulp tissue include various bacteria (8), iatrogenic injury caused by trauma, dental procedures generating thermal stimulation, and chemical agents. Irritation of pulp tissue can result in major changes in pulpal microcirculation that can lead to pulpal necrosis and arrest or cessation of root development (7,14,15).

Dental caries is the most prevalent microbial infectious disease that initially affects hard dental tissues and then the pulpal and periapical tissues (16). In 1894, Miller was the first investigator to associate the presence of bacteria with pulpal disease (17). The role of bacteria in the pathogenesis of pulpal and periapical disease was conclusively demonstrated later by Kakehashi et al. in rats (18). These findings were then confirmed in other rodent studies (19–22), a primate study (23), and in human subjects (24,25).

Dental trauma and restorative procedures can also affect pulpal tissue (26). Thermal injury may occur as a result of tooth preparation or finishing procedures using dry cutting, dull burs, deep periodontal curettage, orthodontic movement, heat generated from polymerization shrinkage of resin composite materials, or lasers and air abrasion devices (27–31). Chemical irritants of the pulp include cavity cleansers such as alcohol, chloroform, hydrogen peroxide, sterilizing and desensitizing substances, as well as some of the substances present in various restorative materials and cavity liners (32,33).

Pulpal inflammation is a complex process involving a wide variety of neuronal and vascular reactions and interactions (34), unique responses of pulpal tissue to irritants, and physiological feedback mechanisms that can cause further injury to this tissue (35,36). Damage to the cells subjacent to the subodontoblastic zone and deeper in the pulp (resulting in abscess formation) constitutes irreversible pulpitis and eventually complete pulpal necrosis (37). Because the necrotic pulp space is relatively inaccessible to the immune response, it becomes a reservoir of infection. Interaction of these irritants with the host tissues results in the release of non-specific mediators of inflammation and immune reactions in periapical tissues (38).

Factors affecting treatment planning

Pulpal status and stage of root development are the major factors in the selection of a treatment plan (8,39). The number of visits required, risk of root fracture, the extent of pulpal damage, restorability of the tooth, finances, and patient preferences are factors that should be considered during treatment planning (40,41).

Based on history, signs and symptoms, radiographic findings, pulpal status, and the stage of root development, various treatment plans may be considered (42). If root development is complete, obturation with gutta-percha can be carried out, although an interim dressing with calcium hydroxide [$Ca(OH)_2$] in the root canal for at least 2–3 weeks before final obturation with gutta-percha is advised (43).

Early pulpal necrosis may result in incomplete root formation and external resorption that will lead to a poor crown/root ratio and increased mobility (44). Even though immature teeth have the greatest potential to heal after trauma or caries, particularly when also the apical foramina are wide open, this group of teeth also has the greatest chance of being misdiagnosed and mistreated (45).

Guidelines for the treatment of traumatic dental injuries (46,47) indicate that efforts should be made to provide short- and long-term outcome assessments for these treatments (41). Treatment for this group of teeth should be oriented toward preserving pulpal vitality in order to return these injured teeth to acceptable normal function, appearance, and repair for better prognosis and prolonged tooth retention (48).

Clinical tests to determine pulp condition

Pulpal conditions and stage of root development are the major factors in the treatment planning for teeth with pulpal and periapical diseases. The time-honored procedures of recording a patient's vital signs during the initial visit (49), taking a comprehensive medical and dental history (50), recording the chief complaint, history of the present illness, signs or symptoms of disease, and extraoral as well as intraoral examinations (51) are well known and accepted. Subjective symptoms such as duration and spontaneity of symptoms as well as irritants that bring on discomfort also provide valuable information (7).

Visual examination of both soft and hard tissues to note the presence or absence of swelling, tissue tenderness, caries, defective restorations, crown discoloration, intra- or extraoral sinus tracts (52), and obtaining a history of trauma are essential procedures during an objective examination of patients (8,47). Transillumination or dye-staining can provide clues to the presence or absence of coronal cracks and vertical root fractures (53). Mobility and periodontal probing along with thermal tests can provide information regarding the health status of the pulp (54,55). However, these tests may not always be reliable immediately after traumatic injury, especially in teeth with open apices (53).

Currently the test that assesses the neurovascular supply to the pulp is best accomplished with the electrical pulp tester (56). The results of this test in traumatized young teeth must be interpreted with caution because the sensory nerves may not yet have developed fully and lack of response does not necessarily indicate pulpal necrosis in developing or even mature teeth (8,57).

Alternative methods for assessing the vitality of the pulp are intrapulpal blood flow recordings using laser Doppler flowmetry and pulse oximetry (58,59). Several invasive experimental methods including radioisotope clearance, H_2 gas desaturation, photoplethysmography, and dual wave length spectrophotometry have also been used to measure the tooth temperature and indirectly determine pulp vitality. The tests currently used are crude and more sophisticated methods are needed to determine the health status of the pulp (60).

Radiographic examination of teeth requires good quality periapical and bite-wing radiographs. These

radiographs reveal the status of the lamina dura and periodontal ligament space and detect the presence and proximity of pulpal caries and the quality of dental restorations (61). The use of cone beam computed tomography (CBCT) and ultrasound imaging should provide more accurate information regarding the condition of the pulp and periapical tissues compared to currently used radiographic techniques and this should result in more accurate diagnoses of and prognoses for pathologically involved teeth (62).

Treatment of teeth with vital pulp and open apices (apexogenesis)

When pulp exposure occurs in an immature tooth, the exposed tissue can heal unaided if protected from further injury, or after the application of bioactive materials (63). Preserving as much vital pulp tissue as possible promotes continued vital pulp functions and avoids abnormal root development (64). Healing and repair of pulpal exposures with predictable long-term pulp tissue preservation in both permanent and primary teeth are possible with a variety of methods (65,66).

The treatment of immature teeth has changed dramatically in recent years as new concepts and materials have been developed (67). Therapeutic apexogenesis or vital pulp therapy (VPT) is the treatment of choice for traumatized or carious teeth with vital pulps and open apices. These approaches include indirect pulp treatment in deep cavities and direct pulp capping or pulpotomy in cases of pulp exposure (41). Many teeth traditionally treated with apexification may now be treated with apexogenesis (68).

Direct pulp capping

Definition

"Pulp cap" is defined by the American Association of Endodontists as "treatment of an exposed vital pulp by sealing the pulpal wound with a dental material such as calcium hydroxide or mineral trioxide aggregate (MTA) to facilitate the formation of reparative dentin and maintenance of vital pulp" (69). This procedure can be used in children with immature permanent teeth (70) and in primary teeth 1–2 years before normal exfoliation (71).

History

Various treatment methods for exposed pulps have been developed over time (72). Direct pulp capping has been practiced for more than 200 years since Pfaff covered exposed vital pulps with gold foil in 1756. From the mid-1800s to the early 1900s, the use of medicaments in pulp therapies involved wide-ranging substances such as asbestos fibers, cork, beeswax, pulverized glass, calcium compounds, and eugenol-based cements (73).

The first recorded use of a formaldehyde-containing medicament was published in 1874 when Nitzel applied a tricresolformalin tanning agent to 8,000 exposed pulps (74). Mixtures containing calcium hydroxide for treating exposed pulp were described later, but the importance and extensive use of $Ca(OH)_2$ for direct pulp capping became popular and were frequently studied by European researchers for the disinfection of infected root canals and vital pulp therapies until the Second World War (75).

Since then, $Ca(OH)_2$ has remained the material of choice against which all other suggested materials for pulp capping have been evaluated (76). Although Hermann is recognized as the originator of this treatment method, Zander & Glass laid the foundation for the use of this material as a vehicle for capping pulp exposures (77).

Good clinical follow-up results were reported in earlier studies advocating phenol for disinfection of the wound site following caries excavation, cauterization of the exposed pulps, and capping with either a thick creamy paste of calcium hydroxide or zinc oxide–eugenol cement (78). In the 1960s and 1970s, glucocorticoids combined with antibiotics were frequently used to control pulpal pain and suppress pulpal inflammation. Reports of poor wound healing and even pulpal necrosis rendered steroids useless as direct pulp capping materials (79).

Numerous experimental studies demonstrate dentinal repair of pulpal wounds similar to that obtained with $Ca(OH)_2$ by a variety of dental restorative materials such as polycarboxylate cement, cyanoacrylate, bioactive ceramics, silicate cement, zinc phosphate cement, resin composites, and MTA (80). Growing optimism is emerging regarding the prospect of using biological and bioactive molecules and macromolecules for the treatment of pulpal exposures (65).

Materials

An ideal material for promoting the repair of pulpal wounds with predictable long-term clinical outcomes should control infection and prevent microleakage. It should adhere tightly to dentin, be easy to handle, and allow the formation of a barrier of mineral tissue (66).

For decades, calcium hydroxide-based materials have been the gold standard for direct pulp capping. They disinfect and cause coagulation necrosis at the junction of necrotic and vital tissues, with mild irritation to the pulp and the formation of a hard tissue barrier (81). Hard-setting calcium hydroxide pastes are less caustic than pure calcium hydroxide. However, they do not prevent bacterial leakage. All calcium hydroxide-based materials have a tendency to dissolve over time and the underlying hard tissue has tunnel defects, which are potential pathways for microleakage (82).

The long-term success rate for $Ca(OH)_2$ ranges from 13% to 96%. This variability might be attributed to the inability of this material to biologically activate odontoblasts or accelerate reparative dentin formation. Repair responses similar to that of $Ca(OH)_2$ have been reported for a number of other materials proposed as capping agents for vital pulp therapy (83).

An alternative to calcium hydroxide-based capping materials is MTA, which was developed by Torabinejad and co-workers at Loma Linda University in the 1990s and has received much attention (84). MTA is biocompatible, has antibacterial properties, seals well, and sets in the presence of moisture (85). Having an almost a 15-year history of clinical and experimental success for various applications, MTA (commercially available as ProRoot MTA) in gray (GMTA) and white (WMTA) forms an essential part of today's armamentarium as a favorable material for pulp capping and pulpotomy in primary teeth (86).

Despite having features similar to those of $Ca(OH)_2$, MTA causes less inflammation, less hyperemia, less pulpal necrosis, and a thicker dentinal bridge (87). With these features, MTA appears to be an alternative gold standard substitute to slower pulp-healing $Ca(OH)_2$ in vital pulp procedures, eliminating some of the disadvantages of $Ca(OH)_2$ such as resorption of the capping material, mechanical instability, and subsequent inadequate long-term sealing ability (88).

A variety of biological molecules, growth factors, enamel and dentin matrix proteins, and extracellular matrix molecules secreted by dentin-forming cells during tooth development can play key roles in reparative dentin formation once released (89). Bone morphogenetic protein (BMP), known as osteogenic protein-1, is a promising material, promoting odontogenic differentiation in large direct pulp exposures in permanent teeth when used as a pulp capping agent (90). Enamel matrix derivative (EMD) may potentially play a role in the calcification of dental pulp tissue in a process mimicking normal odontogenesis (91).

Many "self-etch" systems have become popular over the last decade. When bacteria are excluded, the histological response of total-etched and non-etched compomer-restored cavity preparations shows compomers to be biologically compatible with pulp tissues (92), similar to the protective functions provided by calcium hydroxide-mediated hard tissue repair (90).

Histological comparisons of $Ca(OH)_2$ and resin pulp capping in a recent report by Murray et al. (93) tend to support resin adhesives as an alternative to calcium hydroxide. However, calcium hydroxide apparently stimulates far more odontoblast-like cells. An even more daring goal would be to regain the tooth substance that was lost prior to the pulpal exposure. Stem cells, morphogens or growth factors, and the scaffold of an extracellular matrix are key elements involved in the regeneration of a functional dentin–pulp complex (72).

Animal studies

Because of the variations in infectious load and tissue reactions in clinical cases, it is difficult to mimic modeling of caries-induced pulpitis for wound healing in animal models (94). Invasive pulp treatments in relation to caries followed studies in animal models using various external stimuli (95). Evidence from laboratory animals, typically non-human primates, supports that any material which provides a good seal can facilitate pulpal healing as long as bacteria are eliminated (96,97). While data in animal models are based on pathological changes of pulp tissue and dentinogenetic reactions, animal protocols carried out on rats suggest that capping agents can modulate the pulp wound healing process through the apoptotic regulation of pulp cells (98).

Relationships between pulp capping materials, operative debris, tunnel defects, bacterial microleakage, inflammation, and dentin bridge formation in

non-human primate teeth show bacterial contamination in 18.6% of resin-based composite, 22.2% of resin-modified glass ionomer I, and 47.0% of calcium hydroxide-capped pulps (93). Porosities and defects in hard tissue bridges have been described in the capping of healthy and previously healthy pulps in humans and primates (99,100). The fact that such defects are weak spots and give impaired protection against secondary infections from either breakdown of the surface restoration or along its margins was demonstrated by Cox et al. in a monkey model (101).

Calcium hydroxide-based materials have been extensively used for direct pulp capping because of their potential to induce hard tissue repair or dentin bridge formation and enhance pulpal healing (102). Exposed and contaminated pulps of permanent monkey teeth capped with different materials including $Ca(OH)_2$ do not support the claim that its compounds exert a persistent stimulating effect on the pulp, resulting in eventual pulp space obliteration (103).

Continued physiological root formation was observed in all teeth capped with Calvital and Dycal calcium hydroxide pastes followed by intravenous injections of tetracycline at various intervals in dogs' permanent teeth with incompletely formed roots (104). The capped exposed pulps of Rhesus monkey teeth showed a similar consistent soft tissue healing pattern but at a slower rate at the exposure site with the $Ca(OH)_2$ materials than those capped with Teflon (105). No difference was found between gray and white MTA in the production of calcified tissue when implanted in rat connective tissue (106).

The sealing ability and tissue response of MTA as a pulp capping material have been favorably evaluated in the canine teeth of beagle dogs (107). Furthermore, Pitt Ford et al. capped the teeth of monkeys and verified the formation of a mineralized tissue bridge in all of the specimens except for one (108). In experimental animals, MTA has the capacity to induce consistent, more complete hard tissue repair at a greater rate with a superior, improved pulp tissue and structural integrity than calcium hydroxide-based materials (109).

The histology of pulp reaction to MTA compared with $Ca(OH)_2$ has been described in detail, including examining the proliferation of pulp cells in rat molar teeth. While some authors found no significant differences in pulp healing between the two substances (22), other studies (Fig. 1) found MTA to be superior to $Ca(OH)_2$ (108,109). The pulp reaction of capped monkey teeth to a combination of MTA and BMP-2 was not significantly better than the use of MTA alone (110).

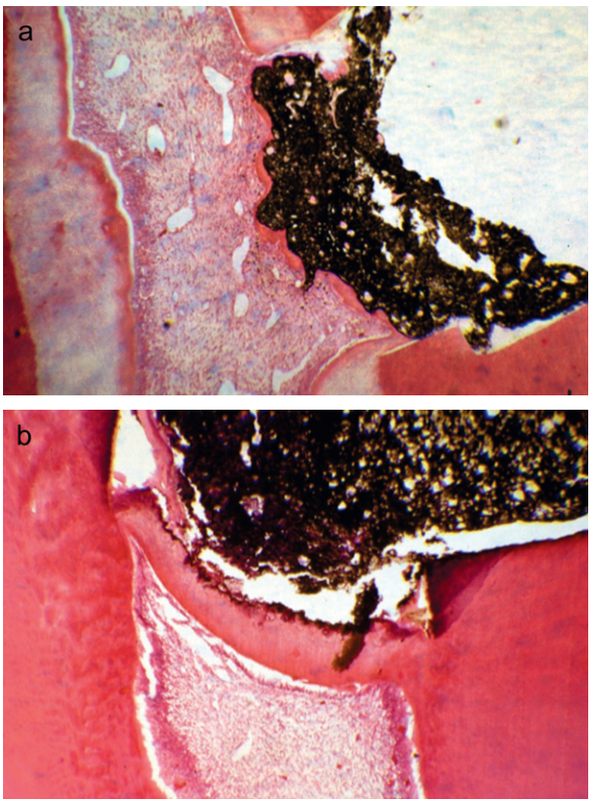

Fig. 1. (a) Histological section of a dog's tooth pulp-capped with calcium hydroxide for eight weeks shows a thin layer of dentin and an inflamed pulp. (b) Development of a solid layer of dentin in another tooth pulp-capped with MTA for 4 weeks. Note absence of inflammation in the pulp tissue. Courtesy of Dr. D. Junn.

Biocompatibility with resin-modified glass ionomer and calcium hydroxide direct-capped exposures on monkey pulps demonstrated similar pulpal healing (111). Hemorrhage control with 2.5% sodium hypochlorite (NaOCl) has been successfully demonstrated in pulp exposures prior to vital pulp therapy (98). The protrusion of pulp tissue into cavities in the mechanically exposed pulps of monkey teeth (80) and the molars of Wistar rats (112) using commercially available adhesive resin systems varied depending upon the materials tested.

Human studies

The study by Brännström & Lind (113) has been a key reference, showing that early enamel lesions in human

teeth lead to odontoblast alterations and signs of pulpal infiltration, in contrast with the operative opinion of Massler (114). The effects of restorative materials and capping agents on dental pulp during wound healing have shown pulpal responses against materials including composite resin (103). The Cochrane review indicates that variation in base materials does not produce any differences (115).

Calcium hydroxide paste itself has been found not to be the critical factor; the tissue necrosis that it induces and which stimulates the pulp is more important (77). When comparing success rates of calcium hydroxide and resin pulp capping procedures, it is apparent that, due to the lack of inherent hemostatic and bactericidal properties of the resin materials, these materials do not perform well (116). Persistent inflammatory reactions as well as delays in pulpal healing and failures of dentin bridging were reported in human pulps capped with bonding agents, in contrast with the results observed in animal teeth (117).

Although both $Ca(OH)_2$ and MTA are good for pulp capping and wound healing in human teeth, MTA has been shown to be superior, safer, and more promising than $Ca(OH)_2$. It induces a dentinogenic process that is faster and more homogenous than that induced by $Ca(OH)_2$ (Fig. 2), promoting the formation of granulation tissue within 3 days, which is a prerequisite for pulp tissue healing (88).

A combination of MTA and EMD might be a potential effective pulp capping agent in facilitating the formation of hard tissue on exposed pulp. It may promote more rapid differentiation than MTA alone, as EMD has been shown to induce reparative dentin formation and odontoblast differentiation in experimental pulp capping studies (118).

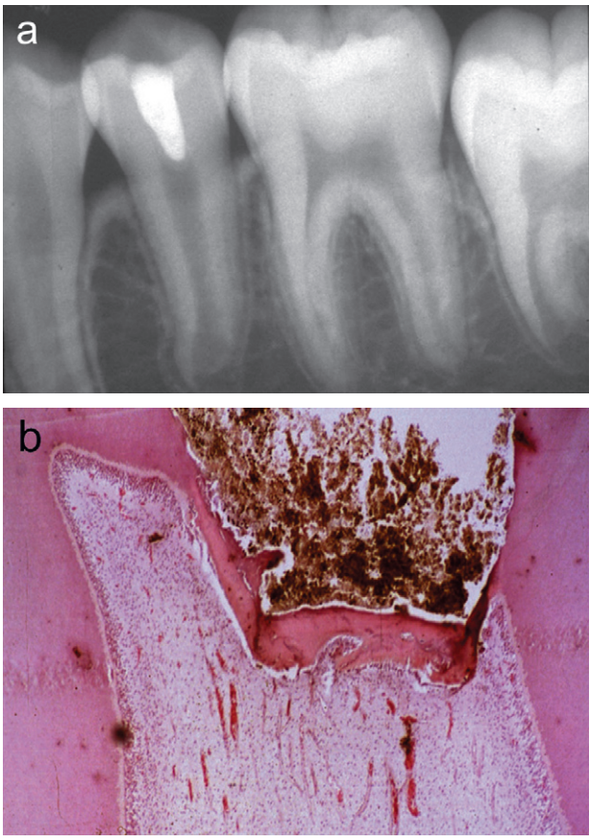

Fig. 2. (a) A premolar tooth with dens evaginatus has been prophylactically pulp-capped with MTA. (b) Histological section of this tooth that was extracted for orthodontic reasons after six months shows an apparent continuous dentin bridge formation a pulp without any inflammation. Courtesy of Dr. E.T. Koh.

Mechanism of action

An important attribute has been that pulpal healing occurs in an environment free from wound infection and that the materials, after the initial exposure to the pulp, become relatively innocuous (66). Initiation of reparative dentin formation might not be attributed to any specific dentinogenic effect, but it appears that the stimulation of the wound healing process is affected by infection control (102).

Bridge formation beneath a pulp capping material could be due to the properties of the capping materials such as sealing ability, alkalinity, and biocompatibility (105). Bovine pulps treated with $Ca(OH)_2$ solutions of varying pH and concentration or with saturated $Ba(OH)_2$ suggest that the effects of $Ca(OH)_2$ are mainly pH dependent (119).

Perforations were treated by partial pulpotomy after exposure for 4, 48, or 168 hours in nine young monkeys, and by direct pulp capping after exposure for 4 or 48 hours in the remaining four animals. After hemostasis, the pulpal wounds were covered with calcium hydroxide followed by conventional amalgam. Conventional histology screening after 1–6 months of the initial and subsequent formation of hard tissue bridges over the wounds showed three categories of initial bridging development differing in nature and rate of formation. A significant difference in the distribution of the two main categories was found

between the two methods of treatment with a similar difference observed when partial pulpotomy was performed after 168 hours compared with that performed after 4 hours. No relationship was found between the initial bridging category and the eventual development of complete dentin bridges (120).

The process of MTA-induced reparative dentinogenesis might primarily involve a "non-specific" wound healing mechanism of the exposed pulp, inducing cytological and functional changes within the pulpal cells, which result in the formation of fibrodentin and reparative dentin at the surface of mechanically exposed dental pulp (121). The application of MTA might provide a healing environment for the regeneration of pulp and dentin by osteoblastic-cementoblastic differentiation of human periodontal ligament cells (HPLCs) (122), but the exact mechanisms of its actions as a pulp capping agent in humans are not completely understood (123).

The overall MTA-induced reparative dentinogenic process is basically similar to the process induced by calcium hydroxide, which follows the proliferation, migration, and differentiation of progenitor cells before matrix secretion at the exposure site, stimulating cytokine production in human osteoblasts (124). MTA does not contain calcium hydroxide; however, it contains calcium oxide, which forms calcium hydroxide with tissue fluids, producing a substance similar to hydroxyapatite adjacent to body tissues (125). An increase of the pH value to approximately 12.5 results in the release of calcium ions during the first few hours; this results in a mechanism similar to that of calcium hydroxide whereby a hard tissue bridge is formed following the development of inflammation and a narrow zone of tissue necrosis in the subjacent pulp (126).

In cell culture studies (124), the bioactivity, biocompatibility, and antibacterial properties of MTA may be caused, in part, by providing a mild calcium stimulus to cells in proximity of the material. These properties may contribute to the healing or regeneration of PDL tissue, which serves as a promising scaffold (127).

EMD has been shown to increase the level of mineralization markers by stimulating the expression of osteoprotegerin. When used as a dental capping agent in dogs' teeth, EMD induces the formation of osteodentin and tubular dentin, and might be one of the inductive agents of odontoblasts (128).

Prognosis

Although controversies exist regarding clinical outcomes, risk factors, primary versus permanent teeth, and optimal treatments (129), numerous pulps that have been extirpated in the past could now be saved through the conservative approach of direct pulp capping (Fig. 3) with high success rates ranging from 93–98% after MTA pulp capping of cariously exposed permanent teeth (130). The overall reported prognosis for direct pulp capping is in the range of 80% when performed under ideal conditions for immature permanent teeth. The prognosis of pulp capping in mature permanent teeth with simple restorative needs is affected by the status of the pulp at the time of the procedure (131). The success rate is markedly different for mechanical exposure and carious exposure; the repair of mechanical exposure produces a 92% success rate compared with a mere 33% for the carious exposures. Most of the failures in these reports remain asymptomatic; the pulp tends to become necrotic slowly (132).

Clinical success is judged by the absence of clinical and radiographic signs of pathosis and the verification of continued dentin deposition both radiographically and clinically (Fig. 4). Hard tissue barriers sometimes can be seen at the treated exposure site as early as six weeks after treatment (133). Different definitions of success and failure must be considered when comparing and evaluating data in clinical studies (85). Secondary caries, perforation, and poor sealing are factors involved in the longevity of failed direct pulp capping (134).

Different potential prognostic factors that can influence the outcome of direct pulp capping include the case selection for a given treatment, stage of tooth development, mode of application of capping biomaterial, length of follow-up periods, presence of an extrapulpal blood clot and proper hemorrhage control, coronal or cervical capping area, time elapsed for placement of a definitive restoration of the pulp-capped tooth, and type of capping material (110).

A well-sealed coronal restoration associated with vital pulp therapy appears to be more important than the material used on the vital pulp, which can withstand the toxicity of most dental materials (83). The presence of bacterial infection of the pulp, or microleakage, is a significant inhibiting factor for the

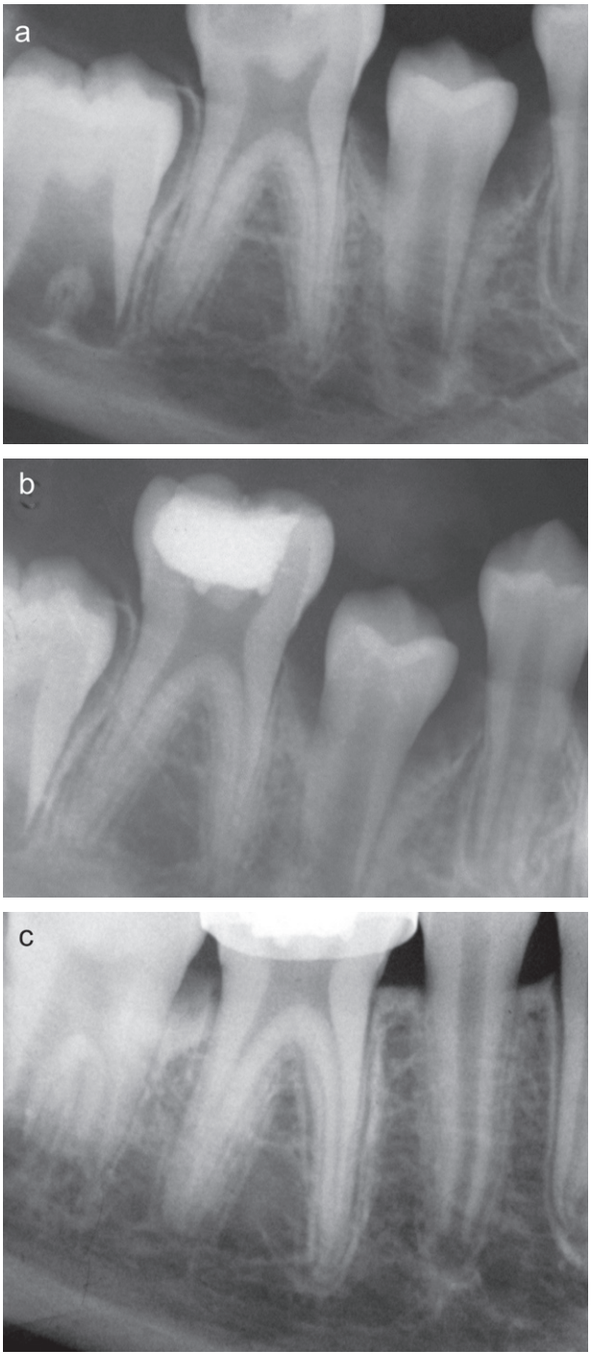

Fig. 3. (a) Pre-operative radiograph of the right mandibular first molar shows the presence of extensive decay. (b) The decay was removed, the pulp exposures were capped with MTA, and the tooth was restored with a permanent filling of amalgam. (c) A post-operative radiograph after 24 months shows normal pulp and periapical tissues. The tooth is asymptomatic and responds to cold.

healing of pulp exposures, showing very limited potential for pulp recovery (71). The influence of age on success or failure of pulp-capped teeth could not be observed in many studies, while operator skill seems to be an important factor (135). Follow-up with 6-month recall time periods for 2–4 years is important in order to assess successful outcomes (136). Controversy exists regarding whether endodontic treatment should be initiated after completion of root development. Preferably, the pulp should be retained unless signs or symptoms of pathosis occur (137).

Advantages and disadvantages

Canal obliteration and internal resorption are the two main pulpal concerns regarding direct pulp capping. These calcific changes of the pulp tissue might signal a biological breakdown in tissue function (140). Although direct pulp capping of mature teeth has less than a 50% chance of success (136), it is universally accepted that vital pulp therapy is the treatment of choice for immature teeth with incompletely developed apices (138).

In a recent systematic review on complete or ultraconservative removal of decayed tissue, Ricketts et al. (139) advise partial caries removal rather than complete caries removal to reduce the risk of carious exposure. This step enables continued physiological dentin deposition and complete root development throughout the length of the root, providing greater strength and more resistance to future vertical root fractures (41). A successful outcome of patient treatment using the new direct pulp-capping materials and techniques is less expensive and requires less treatment time (138).

Pulpotomy

Pulpotomy is the most routinely used treatment for cariously exposed pulps in symptom-free primary molars (141). Its aim is to preserve the radicular pulp so that it can continue to function, stimulate healing, and ultimately preserve arch integrity (142). Its use in mature permanent teeth is a relatively new concept; it is considered unproven for carious exposures (143).

Regardless of the form or type of procedure used, pulpotomy requires a vital radicular pulp (144). This involves coronal pulp amputation to a level where

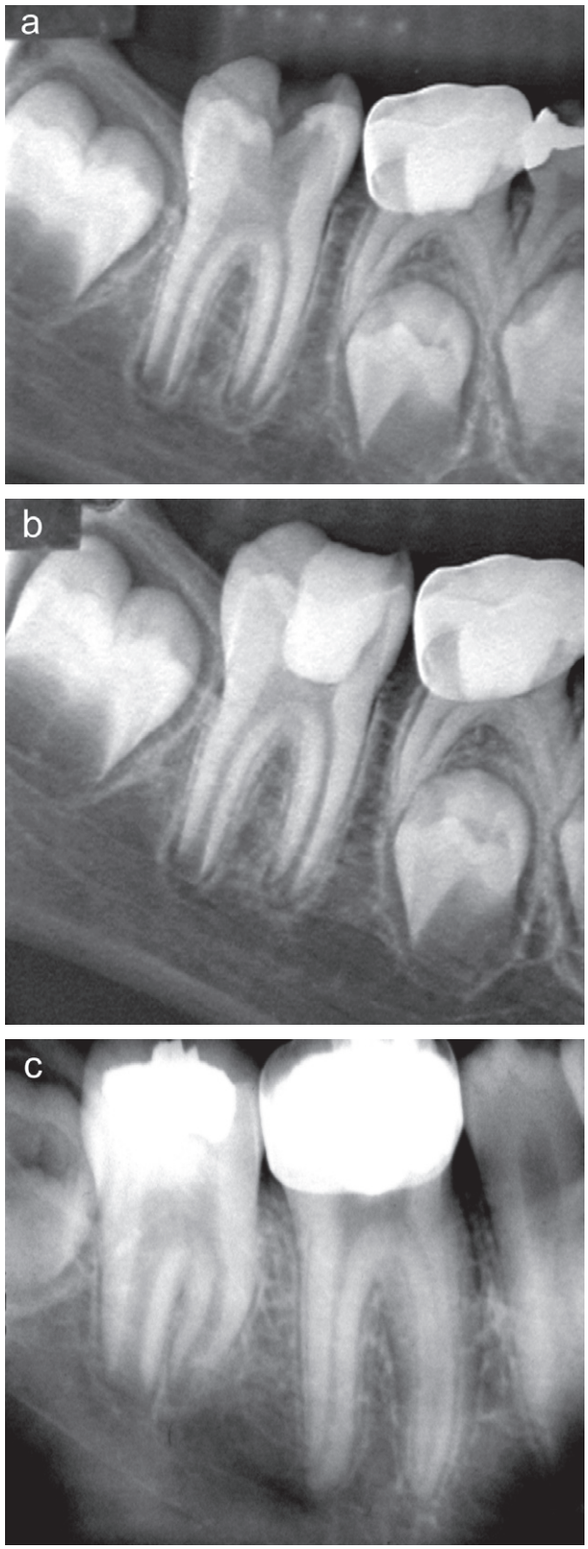

Fig. 4. (a) Pre-operative radiograph reveals the presence of extensive decay, immature roots, and open apices in the first mandibular molar. (b) After removing the decay, the pulp exposures were capped with MTA and the tooth was restored with amalgam. (c) Radiographic examination of the patient 4 years later shows the development of roots and continued apical closure of the root apices in this tooth. The tooth is asymptomatic and responds to cold.

adequate homeostasis can be achieved (145). The remaining radicular pulp tissue is treated with a medicament or electrocautery to avoid adverse clinical signs or symptoms, or radiographic evidence of internal or external root resorption (144).

Partial pulpotomy

If the pulp tissue at the exposure site is not healthy, superficial pulp surgery or a shallow pulpotomy is indicated in order to preserve major portions of the pulp as a functional organ (146). About 2 mm of tissue beneath the pulp exposure is removed (147). Partial pulpotomy has indications similar to those for direct pulp capping in either an immature permanent tooth or a mature permanent tooth with uncomplicated restorative needs (148). Early recommendations were to perform pulpotomies in crown-fractured teeth within 15–18 hours (148), but current recommendations allow treatment regardless of the time expired as long as the pulp is healthy (146).

Definition

Partial or shallow pulpotomy, also known as "Cvek pulpotomy," is defined in the AAE glossary as "the surgical removal of the coronal portion of a vital pulp as a means of preserving the vitality of the remaining coronal and radicular pulp tissues" (69). The rationale for the partial pulpotomy is that, in order for the underlying tissue to remain healthy, the inflamed tissue should be removed so that the exposure site is allowed to heal and be filled with hard tissue bridging (143).

History

The pulpotomy technique became popular with Buckley's publication in 1904, which suggested the use of

equal parts of tricresol and formalin (147). A few years later, Boennecken suggested that his preparation of 40% formalin, thymol, and cocaine was superior to Buckley's solution in pulp amputation procedures (148). While $Ca(OH)_2$ was first used as a dressing on pulpal wounds (80), the defining moment for pulpotomy of an extensively carious primary tooth was a publication in the middle of the last century by Sweet (149,150). The use of formocresolized zinc oxide–eugenol cement was suggested for a single 5-minute application by formocresol (FC) pulpotomy using an effective but weaker strength of FC solution (151).

A technique for superficial pulp surgery involving atraumatic cutting of the pulp tissue has been well established in papers by a number of investigators including Cvek and colleagues (146). Cvek investigated the effects of various levels of coronal pulp surgery in 1978. He termed this as "partial pulpotomy" and used a pulp-cutting technique described by Granath & Hagman (152,153).

Materials used

Restorative materials producing a bacteria-tight seal that protects the wound area from oral ingress are currently available, but the ideal pulp dressing material for pulpotomy has not yet been identified (154). The most commonly used pulp dressing material is FC, an excellent bactericidal agent used for primary teeth with carious pulp exposures, the majority of such teeth being non-vital or questionable for treatment with vital pulp therapy (155). The remaining pulp tissue in these teeth is partially or totally necrotic and is chronically inflamed (156).

Most American pediatric dentists currently use FC pulpotomy to treat asymptomatic caries near the pulp in primary teeth instead of indirect pulp treatment (157). While assessing the data published before 2004 falls short of providing conclusive evidence, this data justifies the "increased concern" for the carcinogenic potential of formaldehyde in humans (158).

Even though its pH value is decreased after use, allowing bacteria to grow in its presence, the proper use of calcium hydroxide can provide an excellent service for an immature tooth with a crown fracture (159). Calcium hydroxide pulpotomy often stimulates the formation of reparative porous dentin that could lead to permanent pulpal necrosis, indicating that it is not an optimal treatment when compared to other techniques (160).

The introduction of MTA has offered an improved method for pulp protection in managing traumatic injuries in the immature dentition (161). A recommended technique using MTA for vital pulp therapy supported by evidence from animal research and clinical experience has been described. It is believed that the use of MTA improves the clinical success of vital pulp healing (107). Pediatric dentistry and endodontic communities agree that FC will be replaced as a primary tooth pulpotomy agent, and MTA is the first choice to take its place (162). Having advantages related to its ability and high level of biocompatibility, MTA appears to perform better than any material with which it has been compared (163). Indirect pulp therapy shows higher long-term success rates than direct pulpotomy except when MTA has been used as a direct pulpotomy material (164).

Animal studies

It is generally accepted that formaldehyde is genotoxic *in vitro*, induces mutations, and damages DNA in bacteria and in human, monkey, and rodent cells (165,166).

The sealing ability and biocompatibility of MTA, as well as calcium ion release by this material (167), seem to be the main factors contributing to the migration, differentiation, cell proliferation, and formation of mineralized tissue (168). It has been shown that calcium chloride ($CaCl_2$), an accelerator added to MTA to improve its sealing ability, favored the repair, formation of cementum, and re-establishment of the periodontal ligament in cases of root perforation in dogs' teeth (169).

When applied to the pulp of a pulpotomized ferret, rhBMP-2 was also found to promote the formation of osteodentin and tertiary dentin (170). Shoji et al. investigated the immediate effects of a CO_2 laser on amputated dental pulps in dogs and found no new dentin over the exposed pulp tissue in the root canal openings after laser irradiation (171).

Human studies

Although pulpotomy procedures have a long history of clinical application, few clinical trials have evaluated this treatment approach (68). There were no

statistically significant differences between four different pulpotomy treatment regimens when used in primary molars (172). Partial pulpotomies in one case report were conducted on two cases of dens evaginatus and teeth were removed after six months as part of planned orthodontic treatment (173).

More than 35% of FC pulpotomies exfoliate six months earlier than non-pulpotomized teeth whereas indirect pulp-treated teeth exfoliate normally (174). FC and ferric sulfate (FS) pulpotomies have significantly lower long-term success rates in the treatment of deep caries compared with indirect pulp therapy (175).

A partial pulpotomy performed on permanent molars with deep carious lesions and pulpal involvement, covered with calcium hydroxide followed by zinc oxide–eugenol, and finally covered with a semi-permanent restoration gained more recognition as a strong possible alternative therapy when pulps were exposed by deep carious lesions and a bleeding pulp was exposed during the excavation process (176). Success of the single-visit apexogenesis supports the use of calcium hydroxide apical closure pulpotomy for continued root development of vital permanent teeth (177).

Cvek and associates assessed the outcome of partial pulpotomy of exposed vital pulps of root-fractured teeth and reported that the pulp wound covered with calcium hydroxide and sealed with zinc oxide–eugenol cement showed healing of the pulp, walling-off of the exposure site with hard tissue, and completed root development in two immature teeth (178).

The results of a prospective study using MTA favor the use of this material as a pulpotomy substance in the treatment of human permanent teeth with irreversible pulpitis. Gray MTA was recommended in this study as a suitable dressing agent for partial pulpotomy in cariously exposed young permanent first molars (179).

While a histological study indicates that electrosurgical pulpotomy performed on primary teeth causes electrocoagulation of the pulp stump, this action does not produce any harmful effects on the apical pulp tissue (180). Another pilot histological investigation on humans suggests that electrosurgical pulpotomy cannot be recommended as a technique superior to FC (181).

Mechanism of action

Pulpotomy protocols vary according to pulp dressing material and treatment objectives. Using FC fixes or denatures the vital pulp, rendering the remaining radicular pulp "inert." Using a hemostatic agent such as ferric sulfate to form a clot barrier might preserve the radicular pulp through minimal inflammatory insult. Lastly, using calcium hydroxide or MTA encourages radicular pulp healing to form a dentin bridge (182).

Under clinical conditions, the matrix formed at the pulp–dentin interface often comprises reactionary dentin, reparative dentin, or fibrodentin formation processes with different biochemical and molecular structures (141). The dental pulp provides the teeth with a nutrient supply for the dentin–pulp complex, innervation and reparative dentin formation during pulpal wound healing, and immunological responses to bacterial infiltration (183).

Lesot et al. (184) as well as Tziafas and colleagues (185) propose two critical requirements necessary for the induction of reparative dentin at pulpal exposure sites, a surface to which pulp cells can attach and attract odontoblast-like cells in order to induce dentinogenic events. The formation of a mineral tissue barrier associated with MTA when mixed with water shows some similarity to the healing after pulp capping with calcium hydroxide. They both provide the formation of calcite granules and underlying bridges of mineralized tissue (167,168). Adhesion and cell differentiation with the subsequent formation of mineralized tissue results from fibrinonectin accumulating around these granules (125).

Prognosis

The probability of healing varies and may increase if several criteria are satisfied, including pre-operative conditions such as in pulps exposed by caries or accident, treatment procedures, a correct clinical diagnosis, or the material used as a wound dressing (82). High success has been recorded when the techniques are used on healthy or reversibly inflamed pulp tissue, where alternative techniques for vital pulp therapy might not provide such high success rates (182). The success of partial pulpotomies for traumatized teeth where the level of pulpal inflammation is very predictable is in the range of 95% (Fig. 5), while the success rate for treatment of carious exposures is currently unknown (148).

Most pediatric dentists believe it is best to enter the pulp and do a FC pulpotomy, even though long-term FC pulpotomy success is significantly lower than

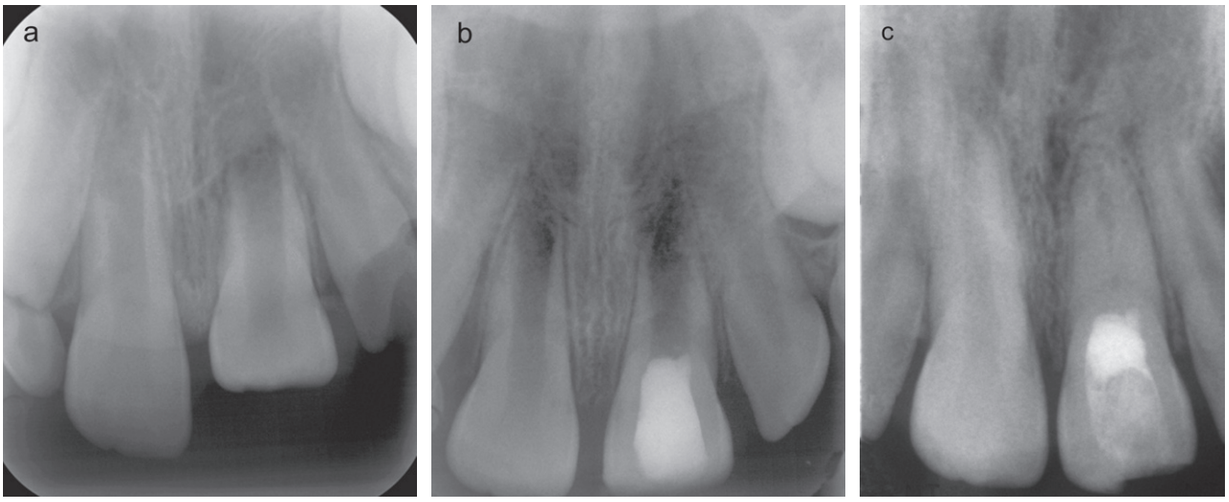

Fig. 5. (a) Pre-operative radiograph reveals the presence of traumatic pulp exposure and open apex in the maxillary left central incisor tooth. (b) After performing a partial pulpotomy, the pulp was capped with MTA. (c) A post-operative radiograph after 36 months shows complete root development and calcification of the root canal. The tooth is asymptomatic.

indirect pulp therapy (174). Partial pulpotomy should be selected as an alternative to direct pulp capping when the extent of pulpal inflammation is expected to be greater than normal, particularly in traumatic exposures longer than 24 hours and for mechanical exposures in teeth with deep caries (143).

All of the requirements for successful pulp capping, such as homeostasis and a bacteria-tight seal, should be met in pulpotomy (143). Sodium hypochlorite or chlorhexidine can be used to facilitate homeostasis, but care should be taken to avoid the formation of a blood clot, which compromises the prognosis (82). In addition, scheduling follow-up examinations using the time intervals and procedures described for pulp capping is important (168). The use of a high-speed handpiece or laser might result in the exposure of a "normal" pulp that would otherwise not be exposed and not need a pulpotomy (141). Glass ionomer caries control (GICC) is indicated in deep carious lesions in order to diagnose their vitality in teeth with signs and symptoms of reversible pulpitis or a symptomless tooth thought to have no pulpitis before instituting any pulp therapy (174).

Advantages and disadvantages

Even though histological assessment of clinically healed pulps that had undergone partial pulpotomy has found that the routine use of pulpectomy after partial pulpotomy treatment is not justified (186), pulpotomy techniques might still have a questionable advantage in 21st century pediatric dentistry because the alternatives to FC pulpotomy have moderate advantages (187). When partial pulpotomy is used on healthy or reversibly inflamed pulp tissue, a high degree of success has been recorded, offering several advantages over direct pulp capping (188). Although no data exists on more mature adult teeth, a limited case series of clinical follow-up treatments show the five-year pulpal survival rate in young teeth with penetrating caries as high as 90% (148).

A large body of published evidence from animal and human studies indicates that formaldehyde is toxic and corrosive, particularly at the point of contact (189). Some investigators claim that, after FC application, fixation occurs in the coronal third of the radicular pulp and chronic inflammation occurs in the middle third, leaving unaffected vital tissue in the apical third of the roots (155). Despite these facts, most American pediatric dentists currently use FC pulpotomy over indirect pulp therapy (157).

Indirect pulp therapy has been shown to have a significantly higher success rate for teeth with reversible pulpitis compared with FC pulpotomy (174). It has a lower cost, with fewer potential side-effects and a

better exfoliation pattern, showing higher long-term success rates than any pulpotomy procedure other than possibly direct pulp capping with MTA (190). The differences in the vital pulp therapy technique when MTA is used in place of calcium hydroxide are important to consider. MTA is placed directly over the pulp wound and the presence of a small amount of blood in the wound area is not a contraindication to placing MTA. Moreover, it is not necessary to re-enter the pulpotomy site later to remove the pulp capping material, as has been recommended for calcium hydroxide pulpotomies (163). Even when caries has not yet caused pulp exposure, pulpotomy is likely to increase the chance of displacing infected dentin chips into the pulp and impair the repair of the pulp when the carious lesion remains 1 mm or more away from the pulp (138).

Full pulpotomy

A full pulpotomy has indications similar to those of a partial pulpotomy except that the pulp in question is likely to have more extensive inflammation (110). Since pulpal inflammation is unlikely to extend past the canal orifices, a full pulpotomy is similar to a partial pulpotomy except that the entire mass of coronal pulp tissue is removed (110,191).

Definition

A "full pulpotomy" refers to the removal of the entire coronal pulp to the level of the root canal orifice(s) or as much as 2–3 mm apical to the orifices (110, 191).

History

Even though it is still considered the most universally taught and preferred pulp treatment for primary teeth, FC has been a popular pulpotomy medicament in the primary dentition for the past 80 years since its introduction by Sweet in 1932 (174). Calcium hydroxide was first used as a dressing on pulpal wounds in 1928 (150). It was proposed in 1962 as an alternative to FC for pulpotomies in primary teeth as it stimulates the formation of reparative dentin (192). Presently, several pulp dressing medicaments and techniques have been proposed as alternatives to FC pulpotomies in primary teeth. They include electrosurgery, laser, glutaraldehyde (GT), freeze-dried bone, bone morphogenetic protein, osteogenic protein, FS, and MTA (193).

Materials used

Despite the toxicity concerns, FC still remains the overwhelming choice for pulpotomy in most schools and by practicing dentists (157). There has been a significant amount of discussion in the literature about the safety of using aldehyde-based products in pediatric dentistry. The International Agency for Research on Cancer classified formaldehyde as carcinogenic for humans in June 2004, leaving the profession to look for alternatives to FC (194). This cancer concern was disputed by Milnes in 2006 because of low-exposure conditions (195).

GT, calcium hydroxide, electrosurgery, corticosteroids, collagens, FS, freeze-dried bone, BMP, and lasers have been proposed as alternative methods and materials (187). Calcium hydroxide was proposed as an alternative to FC for pulpotomies in primary teeth (196) and was the first substance to show the ability to induce dentin regeneration, with a 70% success rate reported (197).

Researchers have proposed MTA as a potential material for use in pulpotomies and direct pulp capping—a suitable replacement for FC (197,198). A randomized clinical trial compared gray MTA with white MTA. Both types of MTA formed thick dentin bridges, but the gray MTA appeared to be better than white MTA and FC as a pulp dressing material (197).

FS has shown promising results as a dressing material for pulpotomies in primary teeth (199). In an evidence-based assessment of FC versus FS, Loh et al. (200) and Deery (201) concluded that both materials are likely to produce similar clinical and radiographic success. The Nd:YAG laser may be considered an alternative to FC for pulpotomies in primary teeth and does not seem to lead to any adverse pulp reactions (109).

NaOCl or chlorhexidine can be used to facilitate hemostasis, but care should be taken to avoid the formation of a blood clot, which compromises the prognosis (82). In theory, electrosurgery as a technique for pulpotomy can be considered a device for vital pulpotomy because it does bypass the historical pharmacological nature of pulpotomy techniques,

thereby eliminating the longuse of carcinogenic, protoplasmic poisons such as FC (156).

Animal studies

With respect to histological responses to complete or partial pulpotomies of inflamed pulps created by *Streptococcus mutans* in 34 immature baboon first permanent molar teeth, complete and partial pulpotomy produced comparable reactions (202). Although a considerable number of clinical trials and laboratory animal studies have been published on this subject, the Cochrane review found that evidence is currently lacking to conclude which technique is most appropriate for pulpotomies in primary teeth (203).

Formaldehyde labeled with radioactive carbon (^{14}C) in rats, dogs, and monkeys was distributed amongst vital organs, showing very small quantities of radiolabeled chemical (204). These findings have been considered overstated by Casanova-Schmitz et al. (205). In dermal studies, formaldehyde was absorbed less readily by monkeys than by rats or guinea pigs (206). On contact with blood, FS forms a ferric ion–protein complex, minimizing the chances for inflammation and internal resorption (207).

Soares observed that the mineralized tissue bridge occurred in 96.43% of the cases after pulpotomy with MTA (208). In 2009, Karami et al. conducted a study using pulpotomized dog teeth. Clinical, radiographical, and histological examinations compared the dental pulp response to trichloracetic acid (TCA), MTA, and zinc oxide–eugenol. They reported that MTA was superior to FC and TCA in treating pulps in dogs (Fig. 6). However, bridge formation was seen in all of the procedures (209).

Investigations of the morphology and localization of calcium hydroxide- and MTA-induced hard tissue barriers in pulpotomized dogs' teeth reveal a larger number of complete (centroperipheral) hard tissue barriers with a predominance of dentinal tubules in the ProRoot MTA group when compared with $Ca(OH)_2$ (210). Salako et al. compared bioactive glass (BAG) with other materials including MTA. The MTA group showed few cases of acute inflammation and evidence of dentin bridge formation at two and four weeks (211).

Animal studies suggest that BMP may induce differentiation of osteodentinocytes, which in turn leads to dentin formation produced on healthy pulps, but not with inflamed pulps (212). However, when da Silva et al. evaluated the pulpal and periapical response of dogs' teeth after pulpotomy using BMP, this procedure resulted in the formation of radiographically visible periapical lesions (213). However, EMD has been successfully used as a pulpotomy agent in non-infected teeth in animal studies (91).

Shoji et al. (171) investigated the immediate effects of a CO_2 laser on amputated dental pulps in dogs and found no newly formed dentin over the exposed pulp

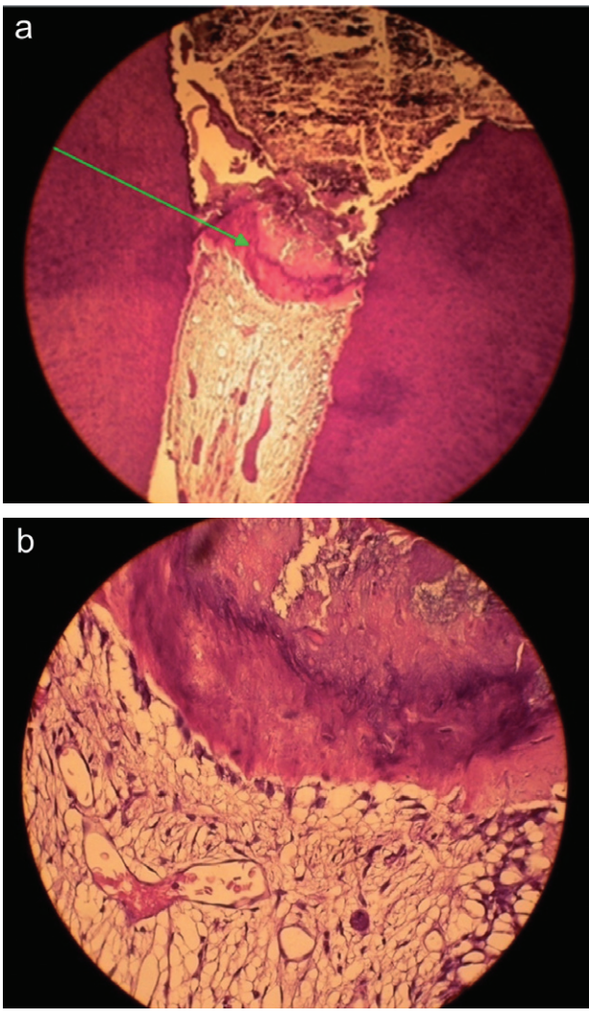

Fig. 6. (a) Histological examination of a dog's tooth after a pulpotomy and capping it with MTA for 2 months shows the presence of a solid layer of dentin over the pulp tissue and the absence of inflammation in the pulp. (b) A higher magnification of the same specimen showing excellent biological response to the pulpotomy procedure. Courtesy of Dr. M. Parirokh.

tissue after laser irradiation. A CO_2 laser was compared with the Nd:YAG laser in a pulpotomy procedure by Jukic et al. (214). They found no detectable damage in the radicular portions of pulps that were irradiated. Kimura et al. (215) evaluated the histopathological effects of the Er:YAG laser on the remaining pulp tissue and periodontal tissues after irradiation. They reported that the high-energy settings caused more damage to the remaining pulp tissue and periodontal tissues than the low-energy settings.

Human studies

Extrapolation of animal data to humans has been confounded by anatomical and physiological differences between humans and animal models (216). The favorable results in young patients demonstrate that pulpotomy treatment in teeth with cariously exposed vital pulps and periapical involvement may be an alternative treatment to root canal therapy (217).

FC has been a popular pulpotomy medicament and is still the most universally taught pulp treatment for primary teeth. No data exist to verify the actual amount of FC delivered to the pulp during the performance of a FC pulpotomy. However, concerns have been raised over the use of FC in humans, and several alternatives have been proposed (141). After FC pulpotomy in 20 children, Zazar et al. (218) found one child showing a six-fold increase in white blood cell chromosomal abnormalities. Holan et al. (219) reported a significantly decreased success rate for FC pulpotomy in primary first molars, raising doubts about the desirability of using this technique on children.

Even though reports generally are of short duration and have small sample sizes, the MTA pulpotomy appears in general to have a higher long-term clinical and radiographical success rate than other pulpotomy types (Fig. 7). All of the MTA-treated molars were 100% successful clinically and radiographically at the six-month observation period. MTA and ferric sulfate have been considered appropriate alternatives to FC for pulpotomies in primary teeth with exposed pulps in controlled clinical studies (220).

There is some controversy about the effect of EMD on inflammation and resorption. Its clinical use on human pulpotomized teeth suggests the need for additional research and further refinement of the delivery system (221).

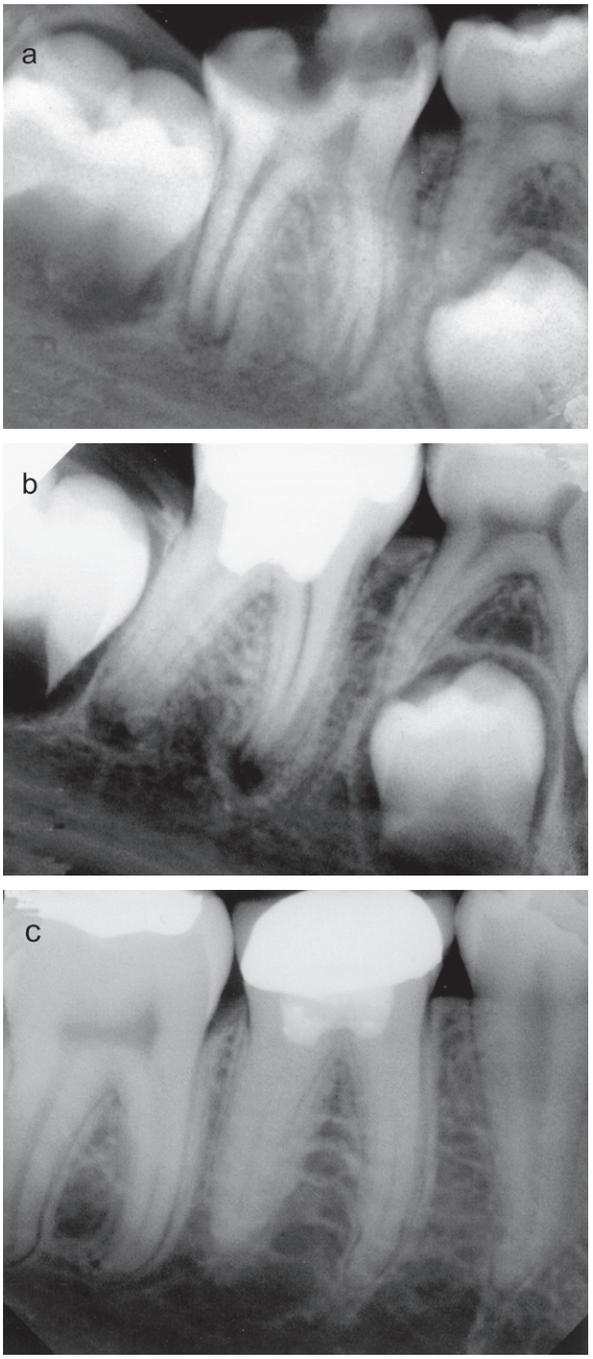

Fig. 7. (a) Pre-operative radiograph of the right mandibular first molar shows the presence of extensive decay and open apices. (b) After removing the decay and performing a pulpotomy, the pulp stumps were covered with MTA and the tooth was restored with a permanent filling of amalgam. (c) A post-operative radiograph after 7 years shows normal periapical tissues and the closure of root canals with dentin. The tooth is asymptomatic and has been restored with a permanent crown. Courtesy of Dr. M. Lindemann.

The use of the Nd:YAG laser in pulpotomies was first described in 1985 (171). Even though few human clinical trials have used a laser pulpotomy for the purpose of outcome comparisons, the laser can remove soft tissue without mechanical contact so that trauma to the residual tissues is avoided (145,172,220). This may be considered an alternative to FC for pulpotomies in human primary teeth (187). Huth et al. compared the relative effectiveness of the Er:YAG laser, calcium hydroxide, and FS with that of dilute FC. Only calcium hydroxide performed significantly worse than FC (222). When the effect of the Nd:YAG laser pulpotomy was compared with FC on human primary teeth, the significantly higher success rate of the Nd:YAG laser led to eruption of the permanent successors of the laser-treated teeth without any complications (223). Saltzman et al. compared a diode laser pulpotomy with MTA in human primary teeth and reported no statistically significant differences between the two groups radiographically or clinically. A larger patient sample size and longer follow-up periods are needed for the laser or MTA pulpotomies to be considered suitable alternatives to conventional FC pulpotomy (224).

Mechanism of action

In response to pulpal wound dressing with FC, various reactions occur ranging from normal pulp tissue to total necrosis, resorption, and apposition of hard tissues (225). $Ca(OH)_2$ is a white, crystalline, highly alkaline, and slightly soluble basic salt that in solution dissociates into calcium and hydroxyl ions. It was also stated that the reaction of calcium ions with carbon dioxide in the tissues might lead to hard tissue bridge formation (168). A necrotic zone is initially formed adjacent to the $Ca(OH)_2$ that must be in direct contact with the tissue in order to allow for this mineralization to occur. Next, either a dentin bridge is formed directly against the necrotic zone or the necrotic zone is resorbed and replaced by a dentin bridge (196,222).

When placed in contact with dental pulp or periapical tissue, MTA behaves similarly to a $Ca(OH)_2$ paste, with similar biological properties but with superior physical properties, such as setting and suitable sealing ability, which promote active hard tissue formation and regeneration of the original tissues (168). The use of BMP in pulpotomy causes morphogenesis, differentiation, healing, matrix secretion, and regeneration by stimulating mesenchymal cells in the pulp tissue to differentiate into odontoblasts and the production of dentin (183).

Prognosis

Pulpotomy is the surgical removal of the soft dental tissue; therefore, an atraumatic and aseptic technique is required for success (187). Reeves & Stanley note significant pathological changes once the caries approach within 0.5 mm of the pulp and when reparative dentin is involved (226). Teeth with carious pulp exposure have a low likelihood of being totally vital and are thus poor candidates for vital pulpotomy (92). Vital pulp therapies are more likely to be successful in chronologically or physiologically young permanent teeth (3). A recent clinical trial of full pulpotomies used to treat symptomatic reversible pulpitis reports a success rate of 90% at 6 months and 78% at 12 months (93). Factors such as the size of exposure, its causes (traumatic, mechanical, or carious), and microbial contamination of the site have been described as determinants of the success of pulp protection (94).

Pulpotomy failures in primary molars are attributed to several factors such as erroneous diagnosis of a chronically inflamed radicular pulp or leakage from large, multi-surface amalgams rather than stainless-steel crowns (198,227). GICC is indicated in carious lesions in order to diagnose their vitality in teeth with signs and symptoms of reversible pulpitis or a symptomless tooth that is thought to have no pulpitis before instituting any pulp therapy (35). For a tooth with an open apex in which the remaining pulp tissue has undergone pathological changes, pulpotomy is contraindicated, particularly when pulp necrosis is diagnosed (95). The key factor in deciding whether to complete a pulpotomy as opposed to a pulpectomy is the ability to control pulpal hemorrhage. In cases in which pulpal hemostasis could be achieved with NaOCl, a pulpotomy can be attempted (187). Care should be exercised to avoid the application of pressure to the pulp (198).

Periodic recall evaluations for 2–4 years are performed at the same intervals recommended for a tooth treated with a direct pulp cap or partial pulpotomy in order to determine success (110). Some authors believe that when the root has developed thick dentinal walls and the apices are closed, a full pulpectomy should be performed (191).

All of the studies comparing MTA with FC show that the use of MTA results in a better prognosis. FS was also better than FC in some studies and similar to FC in others, whereas the three studies with CH showed inferior outcomes (141). The long-term success of indirect pulp therapy (IPT) (3–4 years) surpasses all other pulpotomy studies, with the possible exception of the one long-term MTA study (219).

As with pulp capping, controversy exists regarding whether the pulp should be removed and endodontic treatment initiated after the completion of root development (95). Croll & Killian (228) recommend stainless-steel crowns as the treatment of choice for teeth that have undergone pulpotomy, while Holan et al. (220) suggest a one-surface amalgam if natural exfoliation is expected within 2 years.

Advantages and disadvantages

Even though pulpotomy procedures of cariously exposed pulps in mature teeth remain controversial, it is universally accepted that vital pulp therapy is the treatment of choice for immature teeth (229). Pulpotomies in teeth with incomplete root formation promote normal development of the root complex. This has long-term prognostic advantages resulting in the formation of a great quantity of tooth structure and more resistance to root fractures (230).

Most pulpotomy success decreases over time from 90% or more initially (6–12 months) to 70% or less after three years or more (135). One of the potential dangers with electrosurgical applications is the heat generated, which can cause collateral damage to surrounding structures. Moreover, it is not a technique that would encourage tissue regeneration (180,181). No correlation between FC pulpotomies and cancer has ever been demonstrated. Nevertheless, several studies have reported that the clinical success of FC pulpotomies decreases with time, and the histological response of the primary pulp is "capricious," ranging from chronic inflammation to necrosis (231).

Conclusions

Dentin formation is one of the main functions of the dental pulp. This action results in thickening of the root canal walls and closure of the apical foramen. When the pulp undergoes pathological changes before complete root development, dentin formation ceases and root growth stops. If the pulpal diagnosis is reversible pulpitis, the treatment of choice, depending upon the extent of inflammation, is either pulp capping or pulpotomy. The pulpal wounds heal after application of capping materials (18,63). An ideal material for the repair of pulpal wounds should be biocompatible and prevent microleakage. Various animal and human studies have shown high success rates for vital pulp therapy. These investigations have demonstrated that most young pulps can withstand the initial toxicity of most dental materials (83) and heal as long as the pulp is well protected against microleakage (141). A reparative, biological approach to pulp therapy is therefore preferable to devitalizing approaches (232). Recent attempts to develop more effective pulp capping materials have resulted in the development of new materials such as MTA, which appears to have more predictable effects than previously used materials (109). More clinical studies with larger sample sizes are required to confirm the superiority of MTA (85).

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Biography

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